Development and Applications of Technology for Sensing Zooplankton

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LONG-TERM GOALS

The long-term goal of our research is to improve our ability to observe the ocean's plants, animals, and their physical and chemical environment at critical scales that control how they live, reproduce, and die.

OBJECTIVES

We continue to work towards the development of new tools for studying zooplankton and micronekton in their natural habitat. Our current focus involves extending multi-frequency acoustics to include measurements at more than one angle with respect to the incident sound wave.

APPROACH

Although the use of multi-frequency backscattering methods has clearly improved our ability to study small zooplankton and micronekton *in situ*, the information one can extract from volume scattering and target strength measurements remains limited by the number of independent measurements one can

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obtain with a small number of transducers and by the use of a single independent variable, frequency. A new approach is needed if we wish to successfully address the challenges of remote acoustic classification, to genera first, and eventually perhaps to some level of species identification. The use of simultaneous multi-static, multi-frequency acoustic scattering to detect and classify marine zooplankton offers the potential for obtaining more information than we can currently expect from existing approaches. For example, it is at least theoretically possible to obtain information on scatterer shape, size, and in some cases, even physical properties.

The focus of this research project has been to examine new methods and analysis techniques that will allow us to study zooplankton and micronekton by measuring multi-frequency acoustic scattering at different angles relative to the incident sound beam. We call this approach "multi-frequency, multi-static scattering". Success in developing a new tool that uses this approach depends on making advances in four areas: 1) the development of a sensor geometry that allows us to make high-quality multi-static measurements; 2) developing new methods for modeling bi-static, multi-frequency scattering from organisms of different morphologies and physical properties; 3) validation of those scattering models; and 4) the extension of current inverse methods to include additional dimensions (e.g., the bi-static scattering angle).

We are working towards a transition of what we have learned about simultaneous multi-frequency, multi-static scattering processes in controlled laboratory tank experiments to *in situ* measurements and have built a prototype for use in the next stage of the development effort. Our research efforts have included: 1) making measurements on target objects with known morphology and physical properties to help us identify key characteristics needed for a measurement system for use at sea; 2) measurement and analysis of back- , forward- and bi-static scattering from artificial zooplankton and micronekton size targets in support of efforts to develop realistic models for use in an inverse calculation; 3) examining the potential for extracting information from discrete individual target echoes, and volume backscattering when measured in a small volume; and 4) efforts directed at developing the necessary hardware, firmware and software for measuring multi-angle, multi-frequency acoustical scattering. The nature of the problem has required us to shift our emphasis between these four kinds of effort as we learn more about this multi-dimensional measurement and modeling problem. By combining multi-static scattering with multi-frequency methods we hope to extract better estimates of size than can be made with multi-frequency measurements alone.

WORK COMPLETED

Our approach to this complex problem in sensor development has benefited from a iterative, incremental series of experiments, each of which has been followed by the evaluation of scattering models (e.g., Faran 1951; Hunter, Lee and Waag 1980; Stanton 1988a; 1988b, 1989; DiPerna and Stanton 1991; Ye 1997; Ding 1997; Ding and Ye 1997; Ding *et al*. 1998; Ye 2001) to attempt to understand acoustical signatures we have obtained by direct measurement. Initially, we designed and implemented a measurement system that allows us to examine the multi-frequency, multi-static scattering from objects of known sizes, shapes and material properties in the lab. The test target material properties chosen intentionally had a low contrast with water in density and compressibility. They were constructed to have reasonably simple shapes, e.g., small spheres and cylinders with hemispherical end caps. The targets used are sufficiently realistic to be reasonable analogs of some common marine zooplankters, e.g., copepods and krill, but are not so complex as to be completely beyond treatment with existing analytical and numerical methods. We made measurements, discussed in the Results section below, of target strength versus a non-dimensional frequency and the multi-static scattering angle at several target aspects. A first-cut at the analysis of our lab measurements has been completed, with the result that we have been able to make some judgments about the required characteristics of an *in situ* sensor (e.g., the frequency and spatial resolutions needed to assure that the data collected are not aliased). The advantage of the *in situ* sensor is that it can be used with live animals at sea without having to maintain them in the lab (along with the non-trivial problems of carefully controlling their environment, growing their food, etc.). The hardware for a prototype *in situ* sensor has also been fabricated.

RESULTS

Measurements were made of "echo" levels versus time for broadband acoustical scattering at multiple angles around a molded RTV cylinder with hemispherical end caps (Fig. 1). We use "echo" in a generic sense here, including backscattering, but also meaning signal arrivals from any angle with respect to the incident wave after it interacted with the target (i.e., back-, forward-, and all other angles).

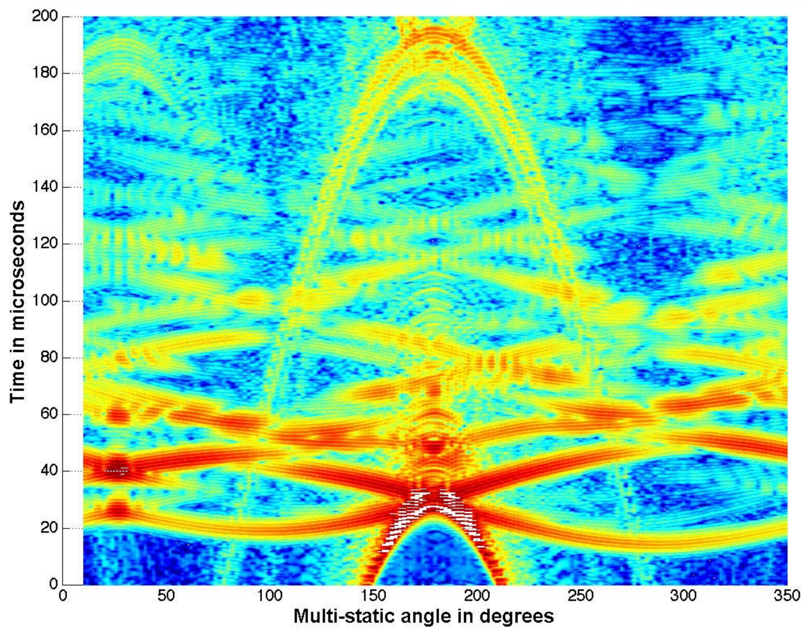

Figure 1: A broadband acoustic pulse produces a complex pattern of echo levels versus time for forward- and multi-static angles. In this figure, the abscissa represents the angle between the source transducer and the receiving transducer, measured in a plane with the target at the origin. The ordinate is time after the pulse trigger, delayed to center the target echoes on the plot. Color indicates echo level on a decibel scale. The target is a molded RTV cylinder with hemispherical ends, with it's principal axis set at -15° from the normal to the incident sound wave. The complex interaction of the incident broadband sound pulse with the target results in numerous distinct echoes at each receiver angle. The pattern of this echo structure versus time and multi-static angle is unique for this target. The arcs with peaks at 180° are artifacts of the experimental setup arising from the direct pulse and a surface reflection.

The target was an RTV cylinder with a diameter of 7.14 mm, and including the two hemispherical end caps, had an overall length of 35.72 mm. The principal axis of the cylinder was positioned in the horizontal plane, rotated to an aspect of -15° from the plane of the incident, broadband pulse (*ca*. 0.300 to 0.800 MHz). Measurements included those between 10° and 350°, but near "back-scattering" angles were excluded because the receiver physically masked the source at 0°. The direct path arrivals at the receiver appear as a hyperbolic arc of high level scattering extending in angle between ca. 145° and 215°. The hyperbolic arc with a maximum near 195 μsec is a reflection from the water surface. The specular arrival from the cylinder segment is near 30° and consists of multiple arrivals at *ca*. 25, 40, 58 and 80 μsec. The remainder of the echo structure in the time delay – multi-static angle plane shown is due to refraction around the cylinder, multiple internal reflections, possible absorption phenomena, creeping waves and coherent interactions between all of the acoustic waves generated during the echo formation process. Taken together they form a "fingerprint" of the target's shape, size, orientation and physical properties. Although the "fingerprint" is quite complex, each feature contains information about the target. The challenge is to extract that information from the "echoes" and to interpret it in biophysical terms that can be used to characterize the object from which the scattering originates.

The target strength of the cylinder and geometry described above can also be displayed as a function of a non-dimensional frequency (ke) and the multi-static scattering angle (Fig. 2).

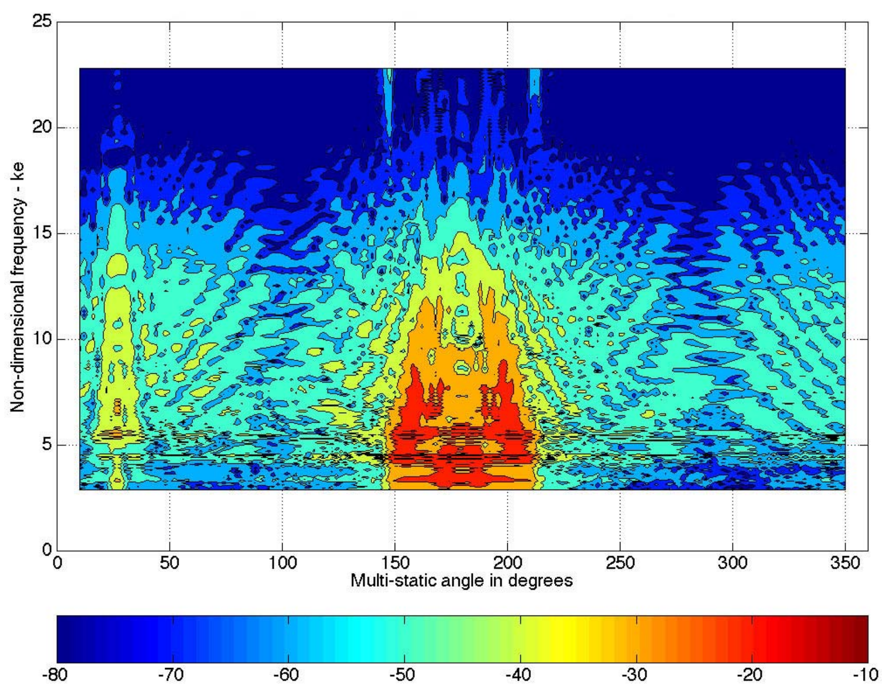

Figure 2: The multi-static "target strength" of the cylinder described in the text is displayed in a plane defined by the non-dimensional frequency (product of the acoustic wavenumber, k, and the cylinder's diameter , e) and the multi-static angle. Higher target strengths occur near the specular angle of 30° and in the forward scattering direction. Useful levels of target strength occur at many angles and non-dimensional frequencies, however, suggesting that a sampled set of these data could be used to extract information about this target.

Measurements of the kind shown in Figs. 1 and 2 were made for spherical and elongate targets of several sizes. The shapes were chosen because of their similarity to the models we have successfully used in multi-frequency inverse calculations for small quasi-spherical zooplankton (the fluid sphere) and elongate micronekton (krill). We were also able to make a few measurements on preserved euphausiids, but their physical properties are quite different than those of live animals and maintaining krill for experiments was not considered critical to learning how to use multi-frequency, multi-static methods at this phase of the project. These measurements were used in defining the parameters and performance required for the design of an *in situ* prototype sensor.

Our prototype multi-frequency, multi-static sensor uses a ring on which a transmitting transducer and several receivers are mounted (Fig. 3). This prototype was designed for use in a lab tank for controlled measurements or for experiments with live zooplankters at sea (e.g., in a cast mode, in a shipboard tank, or mounted on the seabed). It is a first step towards an operational multi-frequency, multi-static measurement system.

Figure 3: A circular frame holds several broadband transducers aimed at the center of the frame. The long black cylinder is a pressure case for electronics. This configuration uses two transmitting transducers in order to cover a wide frequency band (bottom right). Pulses are directed across the diameter of the measurement plane. Multiple receiving transducers are located at known, adjustable, angles in the horizontal plane and are used to intercept echoes when one (or more) scatterer is detected in a very small volume in the center of the circle formed by the frame.

As one makes a cast, or uses the prototype sensor in a static experiment with live animals, a broadband transmitting transducer element is used to ensonify a small volume near the center of the ring. Absent an animal being in the beam, the direct arrival of the pulse at the receiver element opposite the transmitter is used to accurately measure the speed of the sound in the water, a parameter whose precise value is required. The direct pulse arrival is also recorded as a reference waveform. When an organism is detected in the sample volume, multi-static scattering is measured at angles determined by the positions of the receiving elements located around the circular frame. These echoes are sampled and stored for later processing.

Although, for cost reasons, we have only configured the sensor with two transmitting elements, with additional transmitters *backscattering* could also be measured at multiple angles. This would add another set of independent measurements to the scattering data collected. For some experiments additional transducers could be mounted on an arc located above or below the plane defined by the transducer-mounting ring as shown. This would add information that could be used to determine target aspect in the more general 3-D case.

IMPACT/APPLICATIONS

Observation of aquatic animals in their natural environments poses a continuing challenge to scientists working in both biological oceanography and limnology. Our work is focused on the invention and development of new, high-resolution methods and technology for observing zooplankton and micronekton *in situ*. By adding measurements of acoustical scattering at multiple angles to multi-frequency methods, we are attempting to increase the number of simultaneous independent acoustic measurements that are made when scattering sound from marine organisms. Success in applying this new multi-dimensional approach *in situ* should increase the amount of information one may be able to extract by the use of acoustical scattering methods when studying the distribution and behavior of plankton. Marine plankton affects the propagation of both light and sound in the sea. Since many sensors used by naval forces rely on the propagation of either optical or acoustical energy, the distribution of marine life potentially impacts the design and performance current and future naval systems. This is particularly the case for sensors used in the biologically active coastal zone, where both mine detection and ASW operations must be conducted prior to engaging in expeditionary warfare.

TRANSITIONS

Working with Jeff Napp (NOAA/AFSC) under NOAA funding, we have set up a real-time data stream via satellite for zooplankton size and abundance using a TAPS-8 moored at a depth of 17 m in the Bering Sea. The technology development on which this system was based was funded by ONR.

RELATED PROJECTS

Our research and development into advanced acoustical tools for detecting and describing vertical distributions of zooplankton in the coastal zone have resulted in a variety of new tools that are now being applied to a new ONR research initiative on “Layered Organization in the Coastal Ocean” (LOCO). We continue to support our LOCO colleagues with real-time bioacoustics-based measurements of zooplankton distributions, while our own science emphasis focuses on biological processes that may be responsible for generating very small bubbles in thin layers of phytoplankton.

When present, these bubbles can significantly change the propagation and scattering of both light and sound in the sea.

We have continued to provide a low level of support, mostly involving acoustical calibration services, for Pete Jumars (TAPS) (Taylor *et al*. 2005; Abello *et al.* 2005) and Mark Benfield (ADCP).

REFERENCES

Ding, L. 1997. J. Acoust. Soc. Am. 101: 3398-3404.

Ding, L. and Z. Ye. 1997. J. Acoust. Soc. Am. 102: 1977-1981.

Ding, L. *et al.* 1998. J. Acoust. Soc. Am. 103: 3241-3244.

Faran, J.J. 1951. Sound scattering by solid cylinders and spheres. J. Acoust. Soc. Am. 23: 405-418.

Hunter, L.P., P.P.K. Lee and R.C Waag. 1980. Forward sound scattering by small nylon cylinders in water. J. Acoust. Soc. Am. 68: 314-319.

Stanton, T.K. 1988a. Sound scattering by cylinders of finite length. I. Fluid cylinders. J. Acoust. Soc. Am. 83: 55-63.

Stanton, T.K. 1988b. Sound scattering by cylinders of finite length. II. Elastic cylinders. J. Acoust. Soc. Am. 83: 64-67.

Stanton, T.K. 1989. Sound scattering by cylinders of finite length. III. Deformed cylinders. J. Acoust. Soc. Am. 86: 691-705.

DiPerna, D.T. and T.K. Stanton. 1991. Fresnel zone effects in the scattering of sound by cylinders of various lengths. J. Acoust. Soc. Am. 90: 3348-3355.

Ye, Z. 1997. A novel approach to sound scattering by cylinders of finite length. J. Acoust. Soc. Am. 102: 877-884.

Ye, Z. 2001. Recent developments in underwater acoustics: Acoustic scattering from single and multiple bodies. Proc Natl. Sci. Counc. ROC(A) 25: 137-150.

PUBLICATIONS

McManus, M.A., O.M. Cheriton, P.J. Drake, D.V. Holliday, C.D. Storlazzi, C.F. Greenlaw, P.L. Donaghay. 2005. Thin Layers and the Transport and Retention of Marine Plankton. Mar. Ecol. Prog. Ser. 301: 199-215. [published, refereed].

Holliday, D.V. [2006]. Theory of sound scattering from the seabed. Chapter 2 in *ICES Cooperative Research Report on Acoustic Seabed Classification.* [submitted, refereed].